Accelerated Sea-Level Rise from West Antarctica

R. Thomas,[1,2]* E. Rignot,[2,3] G. Casassa,[2] P. Kanagaratnam,[4] C. Acuña,[2] T. Akins,[4] H. Brecher,[5] E. Frederick,[1] P. Gogineni,[4] W. Krabill,[6] S. Manizade,[1] H. Ramamoorthy,[4] A. Rivera,[2,7] R. Russell,[1] J. Sonntag,[1] R. Swift,[1] J. Yungel,[1] J. Zwally[6]

Recent aircraft and satellite laser altimeter surveys of the Amundsen Sea sector of West Antarctica show that local glaciers are discharging about 250 cubic kilometers of ice per year to the ocean, almost 60% more than is accumulated within their catchment basins. This discharge is sufficient to raise sea level by more than 0.2 millimeters per year. Glacier thinning rates near the coast during 2002–2003 are much larger than those observed during the 1990s. Most of these glaciers flow into floating ice shelves over bedrock up to hundreds of meters deeper than previous estimates, providing exit routes for ice from further inland if ice-sheet collapse is under way.

Perhaps half the present increase in global sea level of ~1.8 mm/year is caused by melting of terrestrial ice (*1*). During the 1990s, nonpolar glaciers accounted for an estimated 0.4 mm/year (*2*) and Greenland for ~0.15 mm/year (*3*). Although data from Antarctica are still sparse, they suggest a net loss from West Antarctica equivalent to ~0.2 mm/year and approximate balance in East Antarctica, where uncertainty remains large (*4*). Substantial grounding line retreat (*5*, *6*), thinning (*7*), and acceleration (*8*) have been observed on glaciers flowing into the Amundsen Sea, with small ice shelves now but larger ones in the past (*9*). These glaciers flow into ice shelves over beds well below sea level, and sustained thinning would allow them to float free from bedrock, potentially easing resistive forces acting on upstream ice and thereby leading to further glacier acceleration.

The extent to which ice shelves affect the dynamics of tributary glaciers remains an unresolved controversy within glaciology. Early suggestions that ice-shelf weakening would result in increased discharge from the ice sheet (*10*–*12*) require ice-shelf "back forces" to affect glacier dynamics over long distances. If correct, this implies that "marine ice sheets" with beds deep below sea level may be vulnerable to rapid collapse if their deep beds extend to the coast and if buttressing ice shelves are removed. But if glacier behavior is determined mainly by local conditions, it is almost immune to distant perturbations (*13*, *14*). The behavior of the Amundsen Sea glaciers, recent acceleration of tributary glaciers soon after ice-shelf breakup along the east side of the Antarctic Peninsula (*15*), and rapid acceleration of Greenland's fastest glacier, Jakobshavn Isbrae, after thinning and breakup of its floating tongue (*16*, *17*) may help to resolve this issue, which is particularly important because it could imply far more rapid ice discharge than currently predicted (*1*) from Antarctica in a warmer climate.

Understanding these observations and predicting future glacier behavior requires detailed measurements of surface elevation and ice thickness, but the remoteness of the Amundsen Sea glaciers limited comprehensive measurements until late 2002, when surveys were made from Punta Arenas by CECS aboard a Chilean Navy P-3 aircraft equipped with NASA sensors, including a conically scanning laser altimeter (*18*) and ice-sounding radar (*19*). Four flights yielded measurements of surface elevations (to ±0.4 m) at a dense array of 2-m laser footprints within a swath ~500 m wide, and ice thickness to ±20 m, along a total flight track of 3500 km. Surveys included Pine

[1]EG&G Inc., NASA Goddard Space Flight Center (GSFC)/Wallops Flight Facility (WFF), Building N-159, Wallops Island, VA 23337, USA. [2]Centro de Estudios Científicos (CECS), Avenida Arturo Prat 514, Casilla 1469, Valdivia, Chile. [3]Jet Propulsion Laboratory (JPL), 4800 Oak Grove Drive, Pasadena, CA 91109, USA. [4]Radar Systems and Remote Sensing Laboratory, University of Kansas, Lawrence, KS 66045, USA. [5]Byrd Polar Research Center, Ohio State University, Columbus, OH 43210, USA. [6]Code 972, NASA-GSFC, Greenbelt, MD 20771, USA. [7]Departamento de Geografía, Universidad de Chile, Casilla 3387, Santiago, Chile.

*To whom correspondence should be addressed. E-mail: thomas@osb.wff.nasa.gov

Island (PIG), Thwaites (THW), Haynes (HAY), Pope (POP), Smith (SMI), and Kohler (KOH) glaciers (Fig. 1), where our measurements show much deeper bedrock near the coast than had been estimated earlier (*20*). For the flight running mainly close to the coast between PIG and KOH, the bedrock was on average 400 m deeper than previous estimates (Fig. 2), reaching more than 1 km deeper for the SMI and KOH glacier troughs where no data had previously been obtained, with beds up to 2 km below sea level that may connect to the Byrd Subglacial Basin (BSB). Flights over PIG show its northern side to be shallower than earlier estimates, but its main trunk and particularly its southern tributaries are deeper further inland, suggesting another link to the BSB and the potential for ice-sheet collapse if suggestions that marine ice sheets are susceptible to near-coastal perturbations are correct (*10–12*). Using our ice-thickness measurements, together with velocity estimates for 1996 (SMI, HAY, KOH, POP) and 2000 (PIG, THW) derived from interferometric synthetic aperture radar (InSAR), we find that the entire ice-sheet sector [earlier estimates (*4–6*) only addressed individual glaciers] bounded by and including PIG and KOH discharged 253 ± 5 km^3/year of ice at the time of the velocity measurements, compared to a total annual snow accumulation equivalent of 160 ± 16 km^3 of ice over a catchment area of 393,000 km^2 (*21*).

Satellite radar altimetry data show all surveyed glaciers to have thinned rapidly during the 1990s (*5*, *22*), with thinning rates decreasing from ~2, 3, and 5 m/year near PIG, THW, and SMI grounding lines, respectively, to ~0.1 m/year hundreds of kilometers inland. Comparison of our measurements with surface elevations derived from satellite laser altimeter data acquired by NASA's ICESat (*22*, *23*) in late 2003 and early 2004 shows thinning for each of the four flight lines (Fig. 3), with average values ranging from 0.4 m/year (for the flight primarily over PIG tributaries) to 1.8 m/year (for the flight crossing the seaward ends of THW, HAY, POP, SMI, and KOH), and a mean value of 1.0 m/year for all flights. Although the short time interval implies that elevation changes less than a few tens of centimeters per year may simply reflect natural fluctuations in snow accumulation rates, our results show many areas with changes greater than 1 m/year and a pattern of rapid thinning over fast-moving parts of surveyed glaciers. If the 1 m/year average thinning typifies conditions within the ~60,000 km^2 encompassed by our survey, this alone represents a volume loss of ~60 km^3/year from only 15% of the total catchment area. Although this estimate is approximate, it is consistent with losses inferred from mass-budget calculations if average thinning over the rest of the catchment area is 0.1 m/year, as inferred from satellite radar altimetry data (*22*).

Thinning rates near the grounding lines of all surveyed glaciers reach local maxima exceeding 5 m/year, but with high spatial variability resulting from rapid forward motion of the undulating surface. These values are much higher than the earlier estimates, partly because of the smoothing effect of large radar footprints (several kilometers, versus laser footprints of ~2 m for aircraft and 60 m for ICESat), which results in underestimation of high thinning rates along narrow channels occupied by some outlet glaciers, and partly because of a real increase in thinning. Our results from 2002–2003 and 2004 show thinning along the entire main trunk of PIG (Fig. 4A), averaging ~1.2 m/year between 100 and 300 km inland from the grounding line, or double the value from satellite radar altimetry (*24*) for the period 1992–1999 in an area of smoother near-horizontal ice where the radar measurements should give reliable estimates.

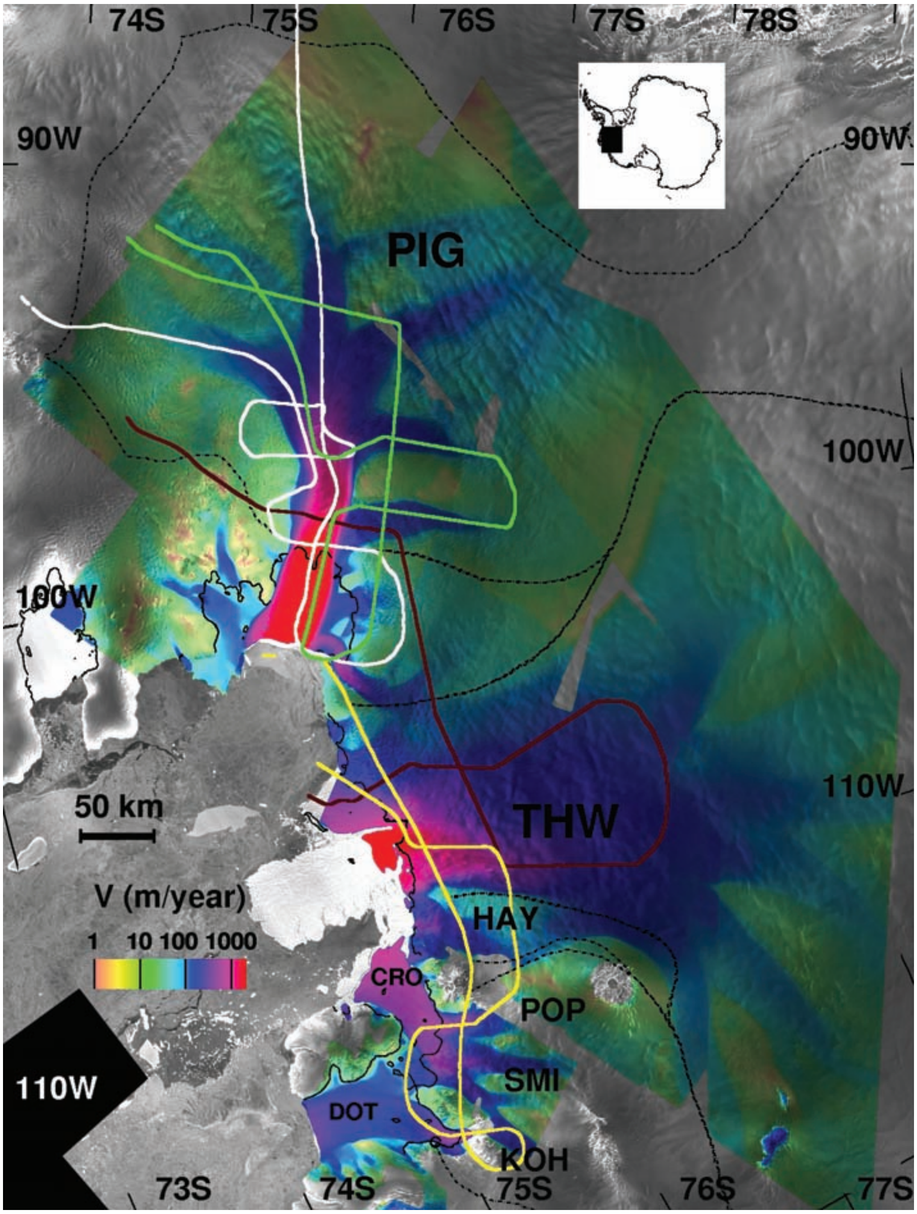

Fig. 1. Part of West Antarctica, showing ice velocities (on a logarithmic scale) derived from 1996 European Remote Sensing Satellites 1 and 2 (ERS-1/2) interferometric radar data (*21*), overlaid on a radar image from Radarsat (*28*). The four CECS/NASA flight lines over Pine Island (PIG), Thwaites (THW), Haynes (HAY), Pope (POP), Smith (SMI), and Kohler (KOH) glaciers, and Crosson (CRO) and Dotson (DOT) ice shelves, are shown in white, brown, yellow, and green lines. Boundaries of catchment basins are marked as thin broken black lines. Grounding line positions in 1996 inferred from ERS-1/2 are shown as thin continuous black lines. Inset shows location in Antarctica.